UNIVERSITY OF DELAWARE
CENTER FOR COMPOSITE MATERIALS
INTERNATIONALLY RECOGNIZED EXCELLENCE

OFFICE OF NAVAL RESEARCH

VIBRATION NONDESTRUCTIVE INSPECTION OF LARGE-SCALE COMPOSITE STRUCTURES

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UD-CCM

Report Documentation Page

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Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

History

1D GSM w/ MS (Colin)

Steel beam

Composite beam

1999

/ MS

/ MS

Composite panels, hull structure, & bridge

FEA &

Commercial Accel.

2000

1D GSM w/ ODS (USNA)

2D GSM & 1D GFM w/ ODS

Quasi-2D GSM (USNA)

2001

uasi-2D GFM

Munition

Strain gage

Fiber optic s

Wireless sensing

SSM

Piezo-electric actuators

Automatic health monitoring

Overview

2D GSM

- Theory in 1D vs. 2D
- Statistical treatment
- Results from FEA and lab tests

Application to CIRTM Corner Structure for Director's Room

- Types of sensors (Accelerometers, Strain gages)
- Effect of frequency range
- Method of excitation (Multi-spots, One spot)

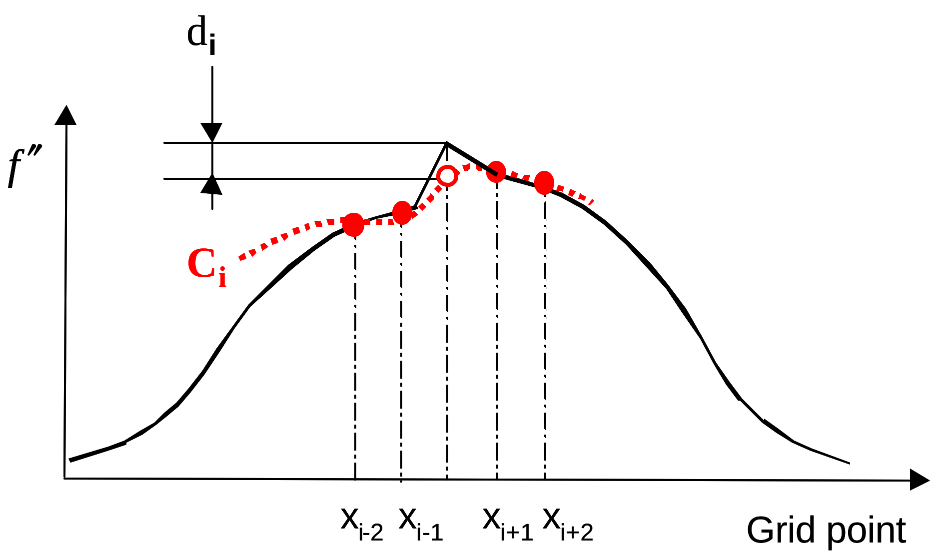
Application to Composite Bridge (Bridge 1-351)

- 2D GSM results from data obtained year 1999~2002
- Testing plan for year 2003

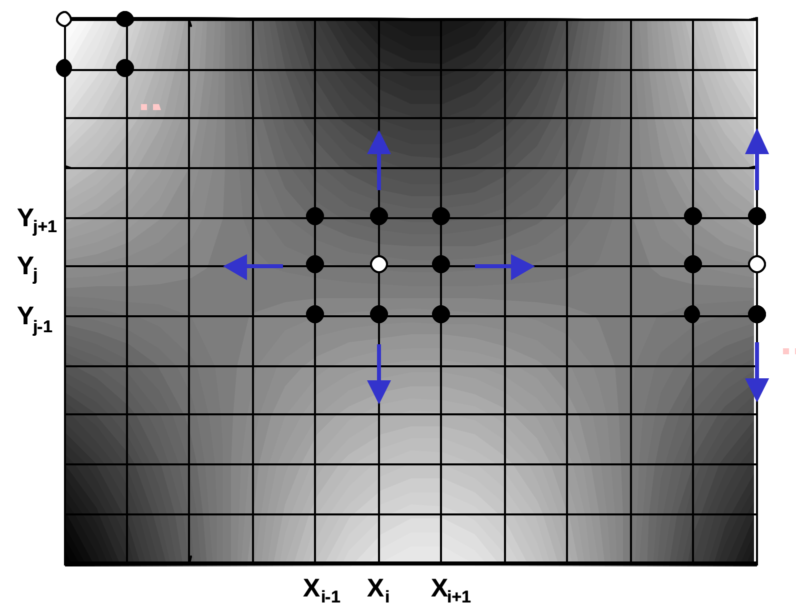
Conclusion/Future Work

Gapped Smoothing Method
(1-D vs. 2-D)

1-D GSM



2-D GSM



$$\nabla^2 y_{i,j} = \mathbf{g}_{i,j}{}^T \mathbf{?}_{i,j}$$

$$\mathbf{g}_{i,j}{}^T = [1, x_i, y_j],\ \mathbf{?}_{i,j}{}^T = [a_o, a_1, a_2]$$

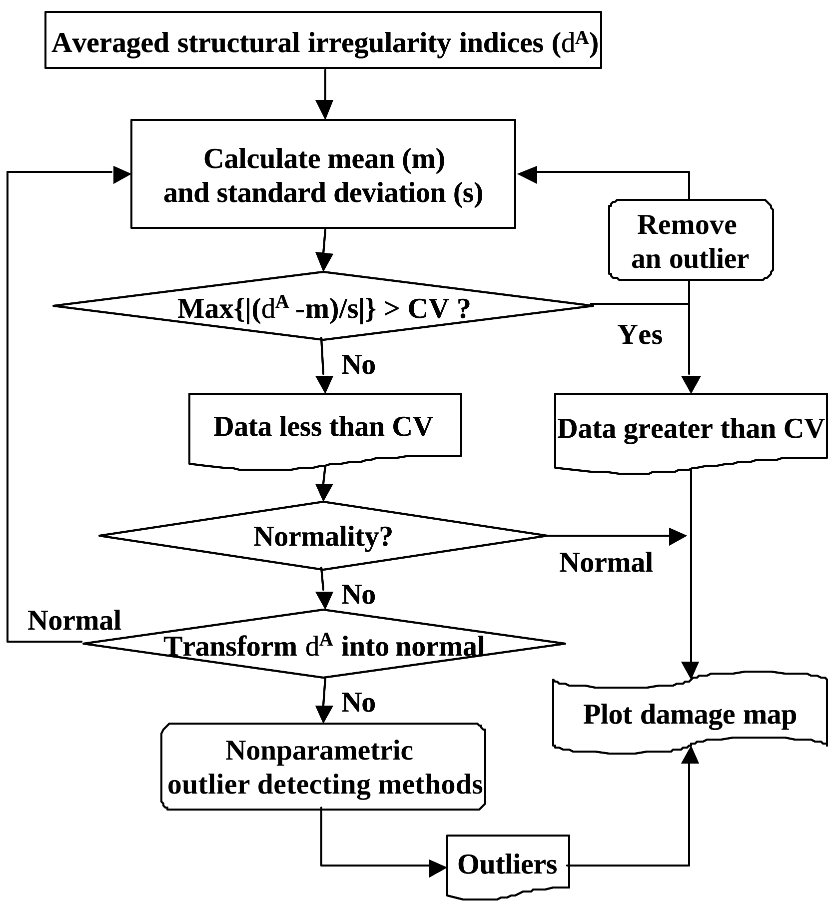
Structural Irregularity Index

=Curvature Shape – Smoothed curvature shape

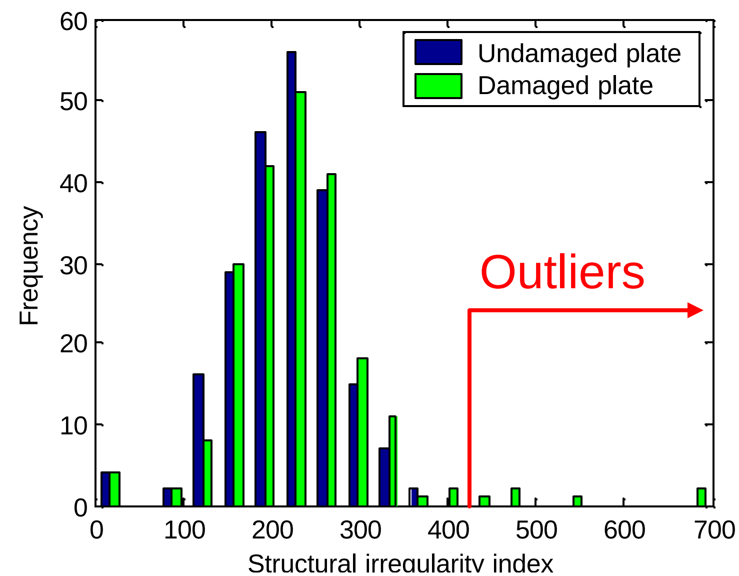
Statistical Treatment

Objective: Filter out noise to obtain only the area of damage with a confidence level CL

Flow chart for outliers detection



Histogram of structural irregularity indices



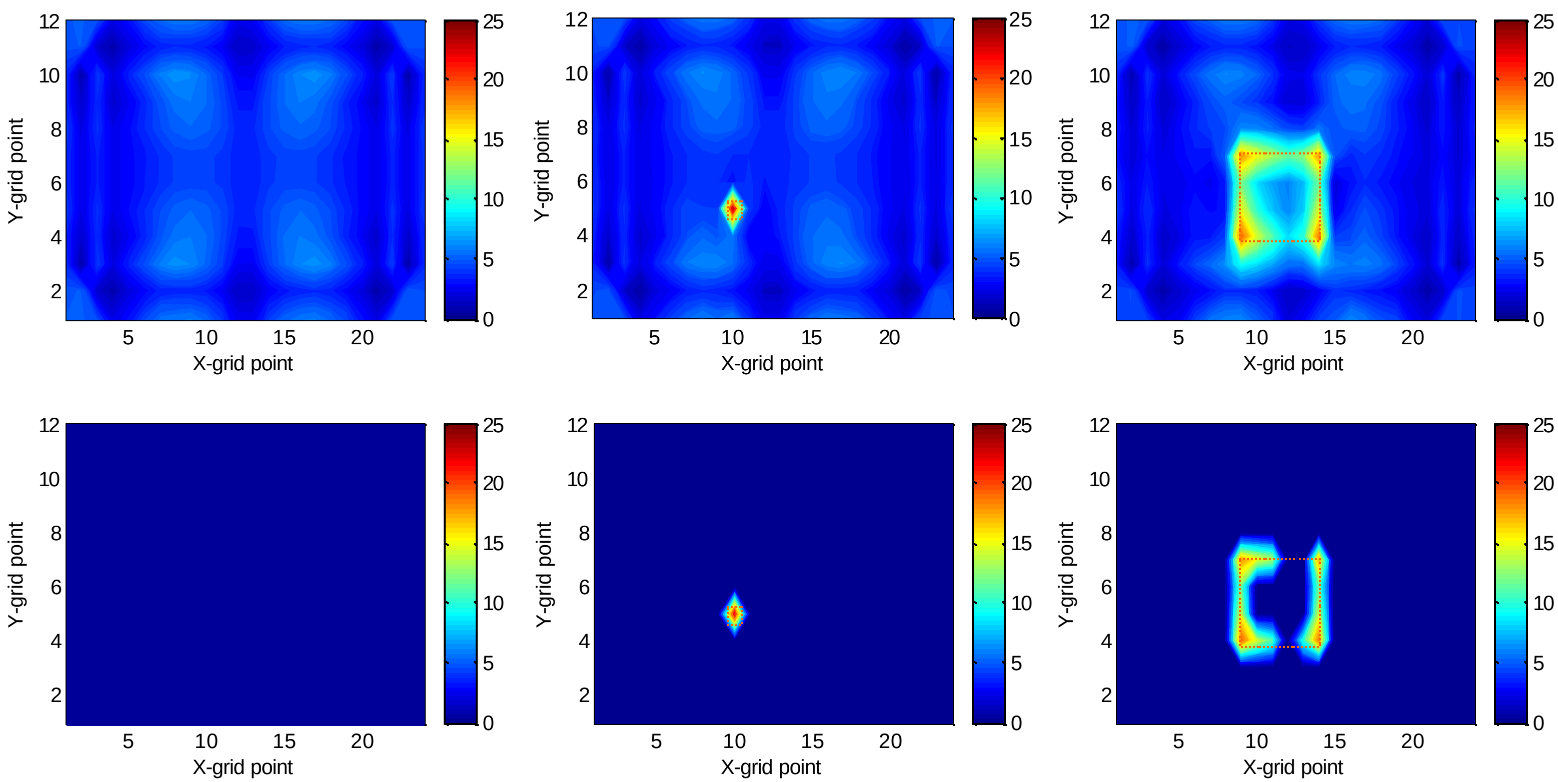
Grubb's outlier detection method

$$CV = \frac{t \cdot (n-1)}{\sqrt{n \cdot (n-2+t^2)}}$$

FEA Results
(Large vs. Small Damage)

SII

SII after Statistical Filtering (95% CL)



No damage

Modulus reduction in small area

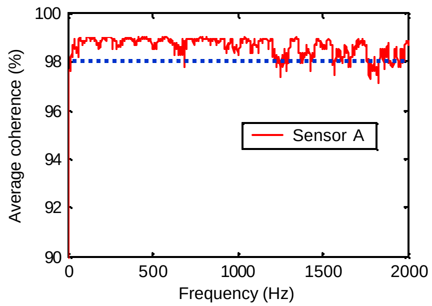
Modulus reduction in large area

- Statistical filter removes data when there is no damage
- Algorithm detects only perimeter of damage area

Lab Testing: (Composite Plate - Multiple Damage Locations)

Definition of SII ? $|\Delta f''|$ vs. $(\Delta f'')^2$

Coherence function

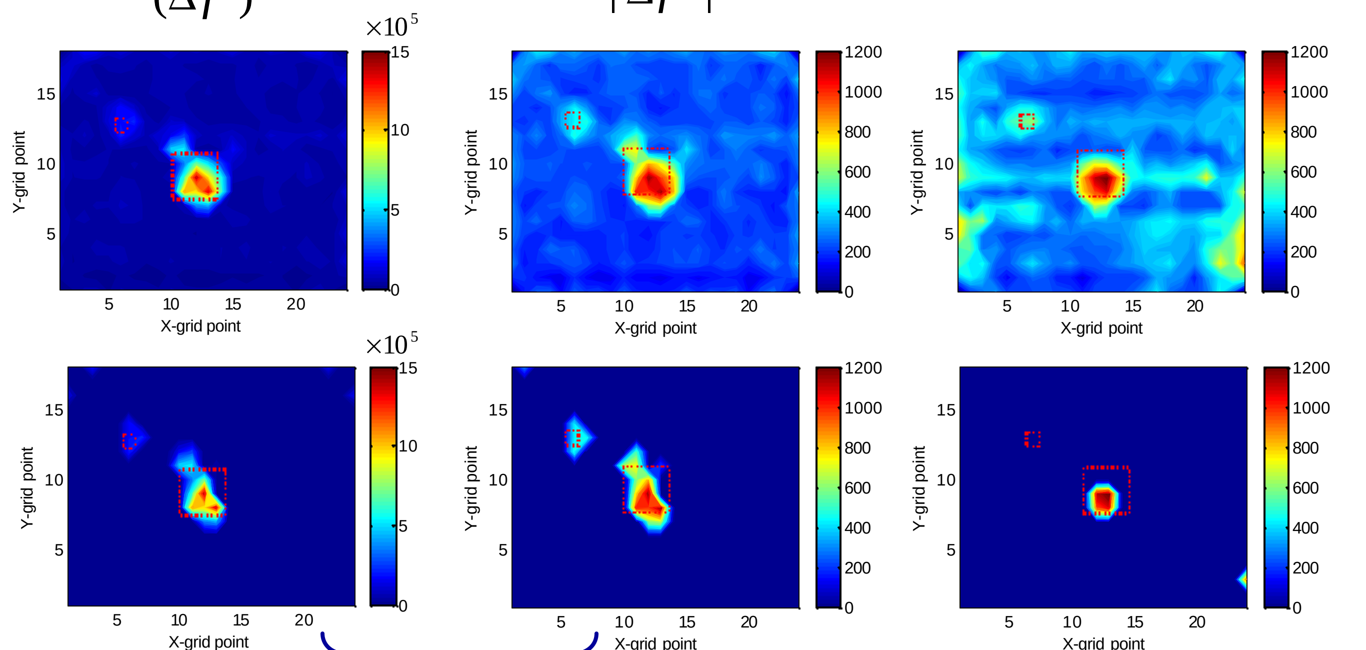


Frequency range: **100~2kHz**

$(\Delta f'')^2$ $|\Delta f''|$

SII

SII after Statistical Filtering (95% CL)

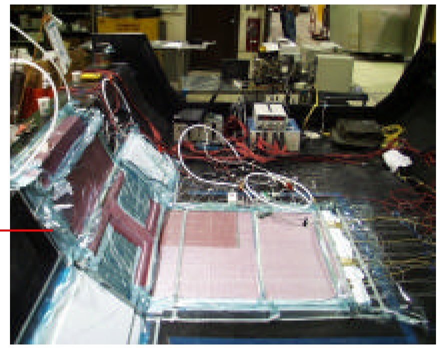


Two delamination with ODS data

Two delamination with MS data

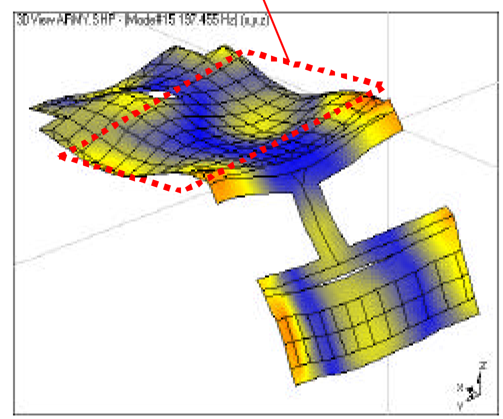
- Squaring suppresses noise as well as secondary damage
- Noise can be filtered out by statistical treatment

Lab Testing
(Composite Hull Structure)



VARTM Manufacturing process

The data used



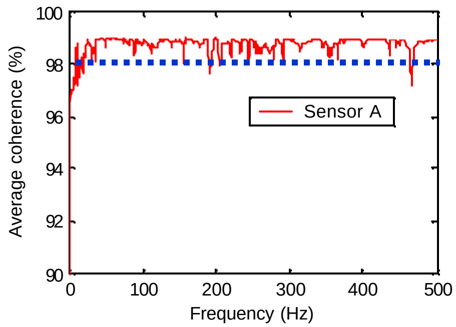
Dry spot

Inside surface

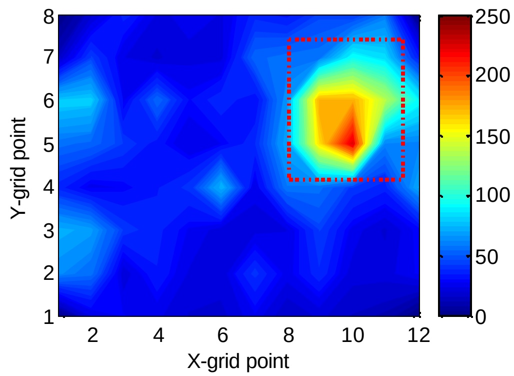
Outside surface

Lab Testing Results (Composite Hull Structure)

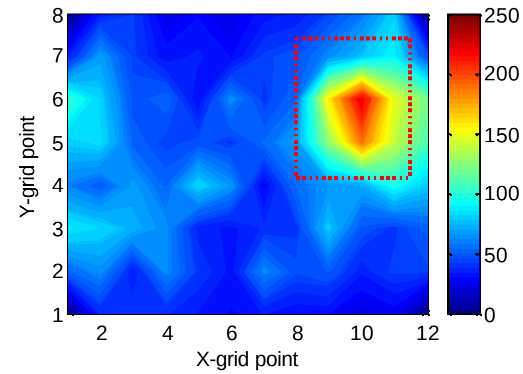
Coherence function

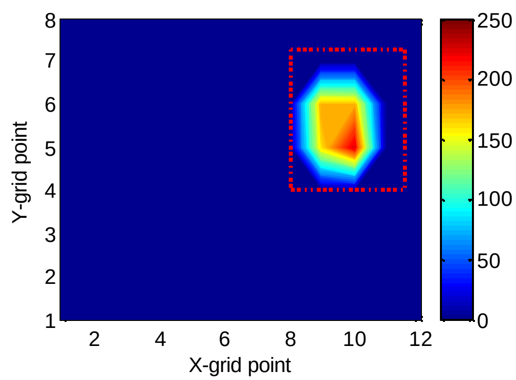


Frequency: **50~500Hz**

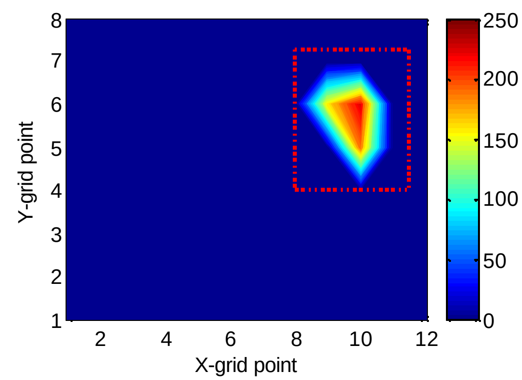


SII





SII after Statistical Filtering (95% CL)



Dry spot area with ODS data

Dry spot area with MS data

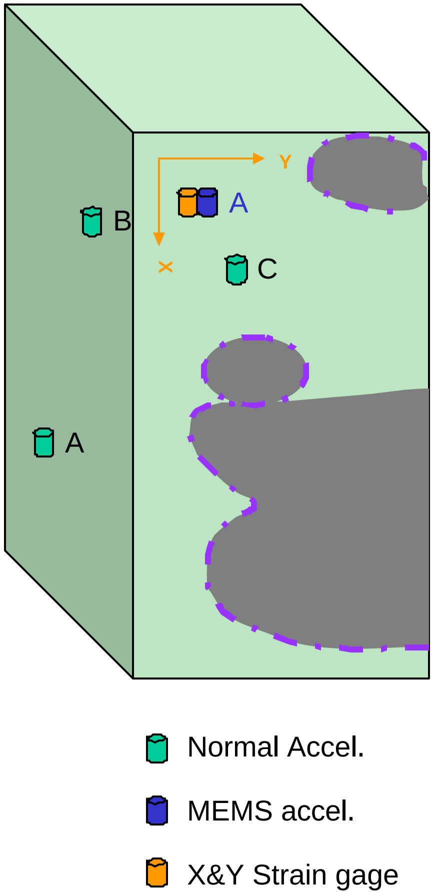
- Both ODS and MS data detected the dry spot
- Using ODS data shows less noise

Large-Scale CIRTM Structure

Objective:

Apply NDI techniques to large-scale composite structure

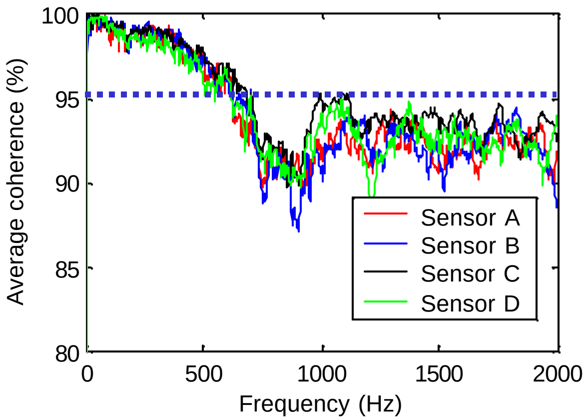
Study on effects of sensor type and location of sensors

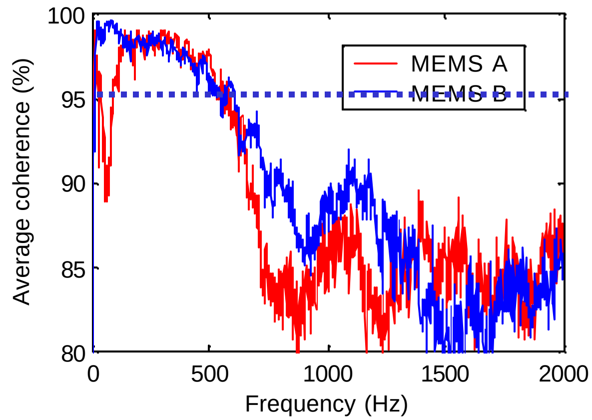


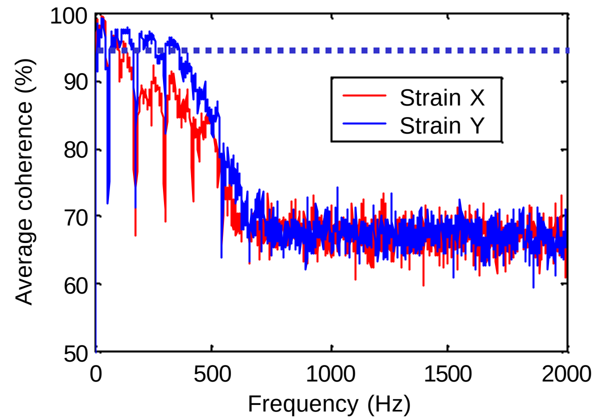
Fabricated by

Coherence for CIRTM Structure

Coherence functions







Commercial accelerometers — **20Hz~600Hz**

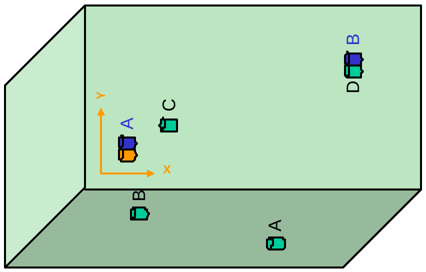
MEMS accelerometers — **100Hz~500Hz**

Strain gages — **5Hz~150Hz**

Effective Frequency Range:

SII Results for Individual Sensor (Frequency: 50~500Hz)

SII with sensor type and location (16 by 9 grids:)

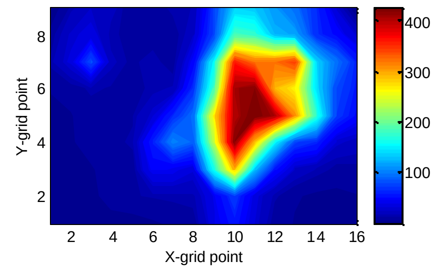


Results:

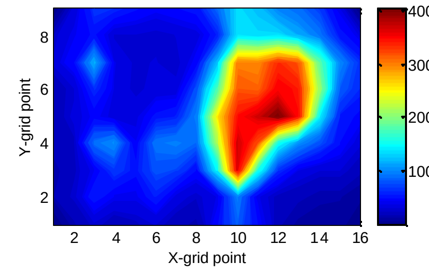
- All sensors detect damage areas
- But sensors located on large delamination can not detect smaller defects

➔ Multiple sensors are needed to detect all defects

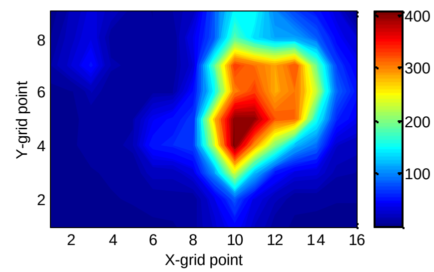
Accel. A



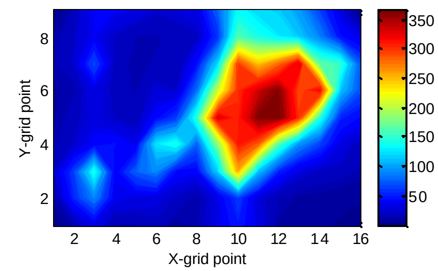
Strain_X



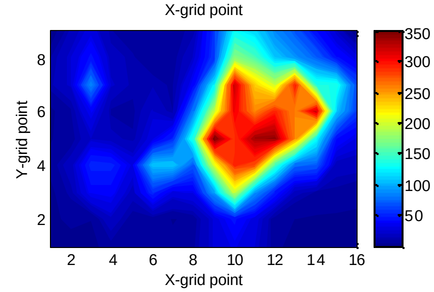
Accel. B



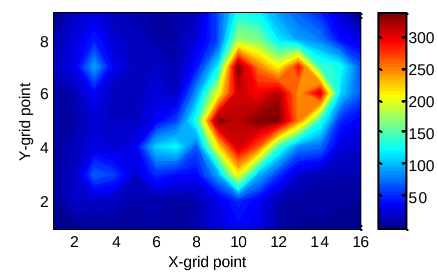
Strain_Y



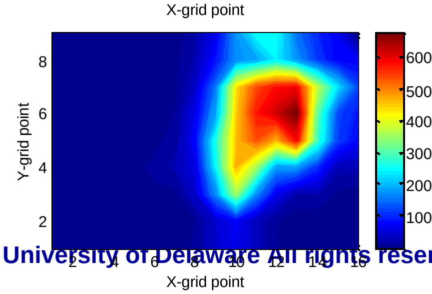
Accel. C



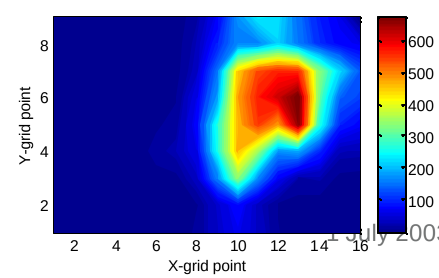
MEMS A



Accel. D

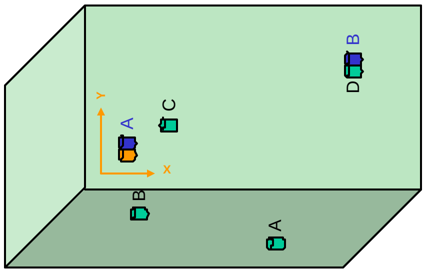


MEMS B

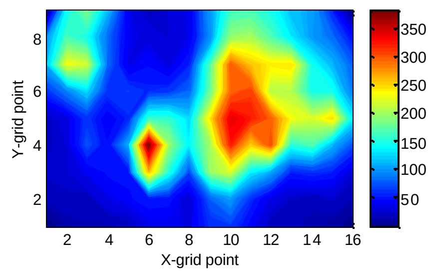


SII for Medium Frequency Range (Frequency: 100~1kHz)

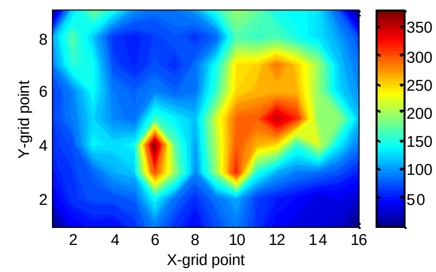
SII with sensor type and location (16 by 9 grids)



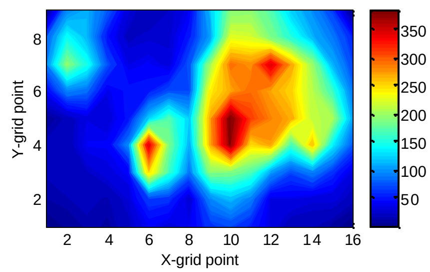
Accel. A



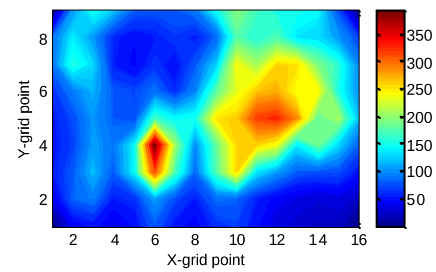
Strain_X



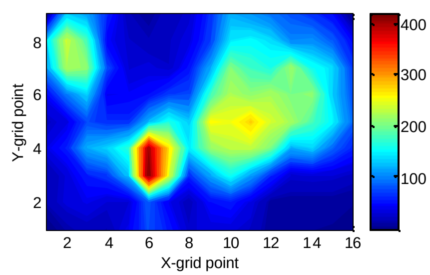
Accel. B



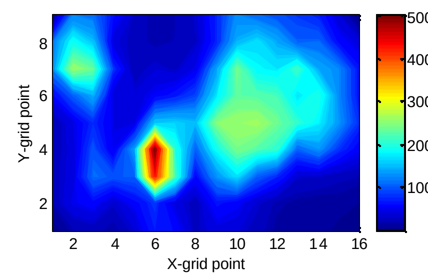
Strain_Y



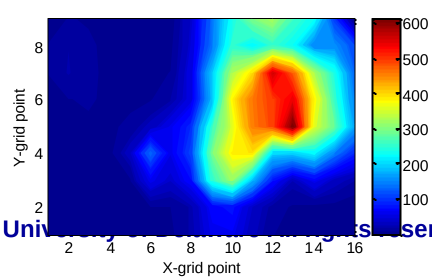
Accel. C



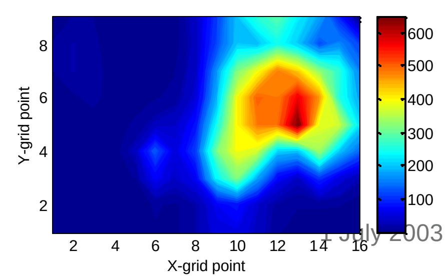
MEMS A



Accel. D



MEMS B

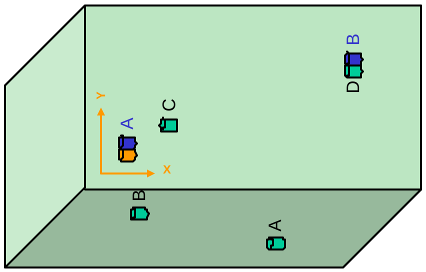


Results:

- Medium frequency range is more sensitive to smaller defects
- The sensor next to damage can detect better the damage (Compare Accel. C & D and MEMS A & B)

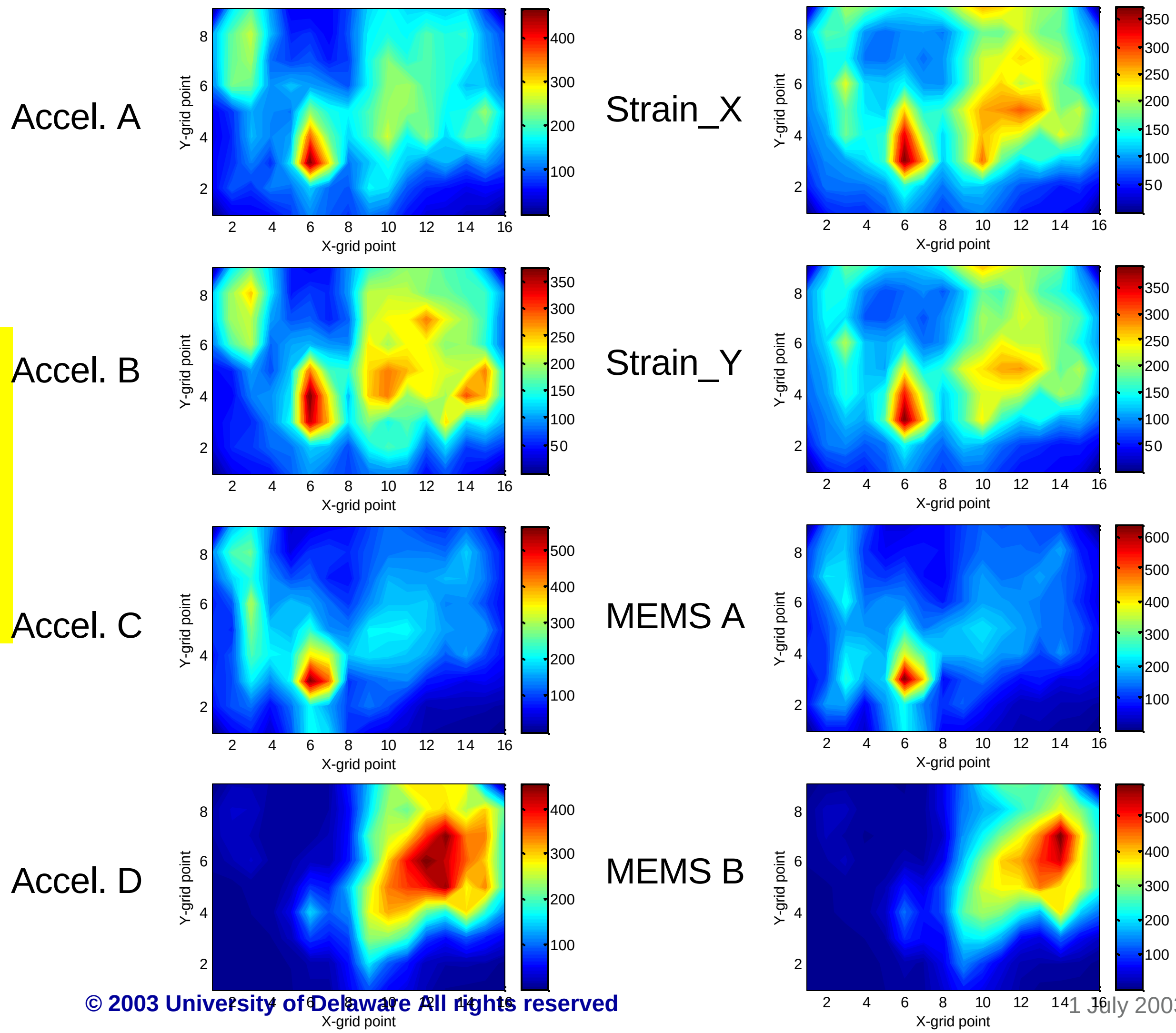
SII for High Frequency Range (Frequency: 100~2kHz)

SII with sensor type and location (16 by 9 grid)



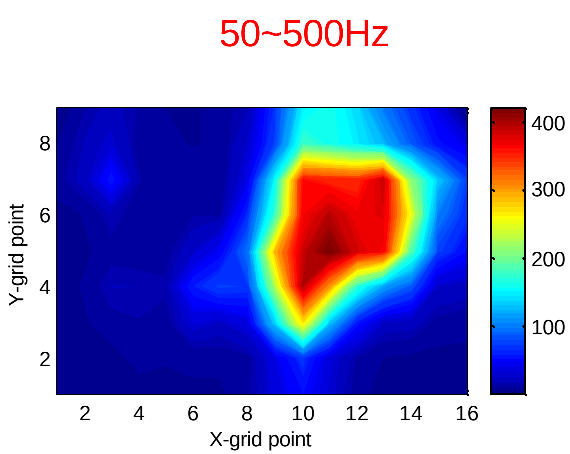
Results:

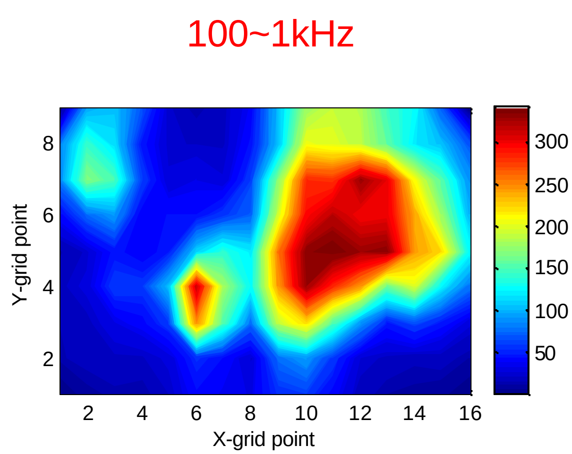
- Noise due to low coherence above 1kHz reduces sensitivity
- Find optimum frequency range for each sensor selection

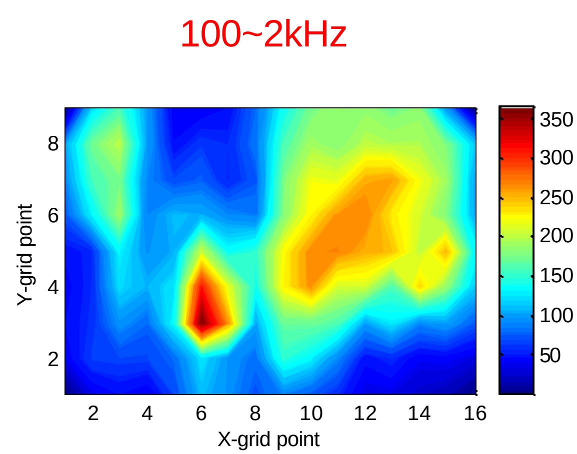


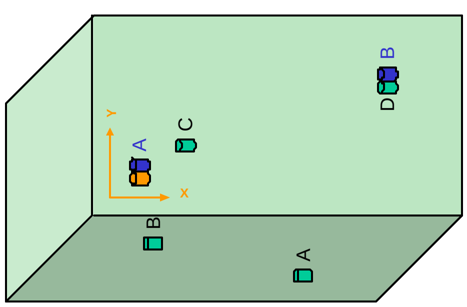
Results for CIRTM Structure (Frequency Range)

Results with sensors A+B+C+D (16 by 9 grids)







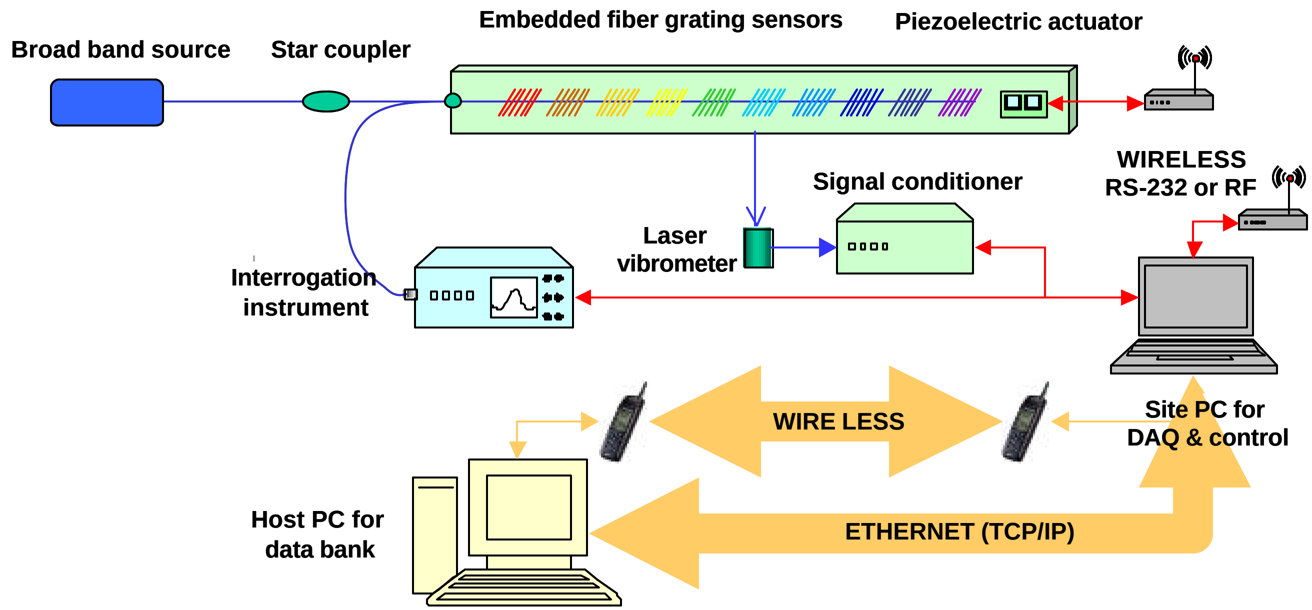


Results:

- Summation of sensor response results in better defect detection of all damages
- Higher frequency is more sensitive to smaller damage but has more noise
- Statistical treatment cannot be applied ← Assumption: Damage area is small compared to total area.

Automation

Motivation: To monitor the condition of structures in real time while in service



AUTOMATED ACTUATORS:
1. Automated impulse hammer
2. Piezoelectric film
3. External car/wind

SENSORS:
1. Smart materials
2. Embedded fiber optics
3. Piezoelectric films
4. Surface mounted strain gages
5. Laser vibrometer
6. Doppler type sensors
(radio, ultrasonic, light)

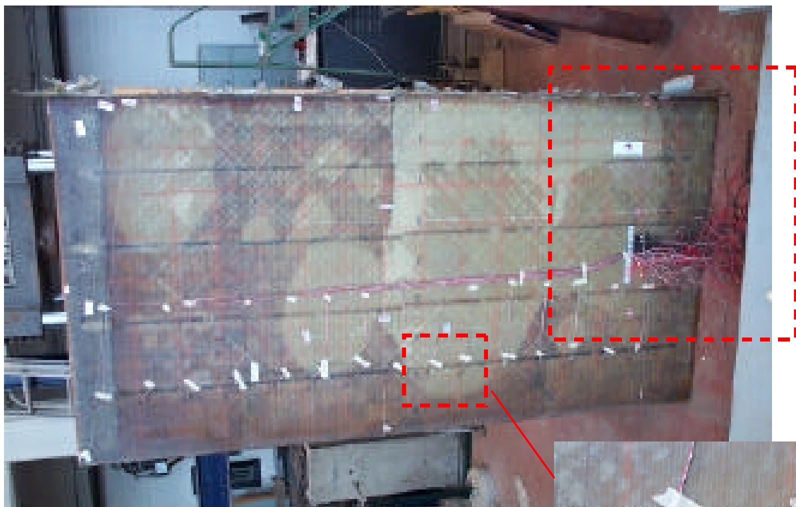
DAQ:
PC-controlled
data analysis

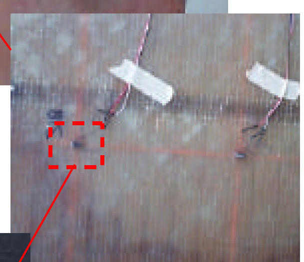
REMOTE MONITORING:
1. TCP/IP
2. Wireless RS-232

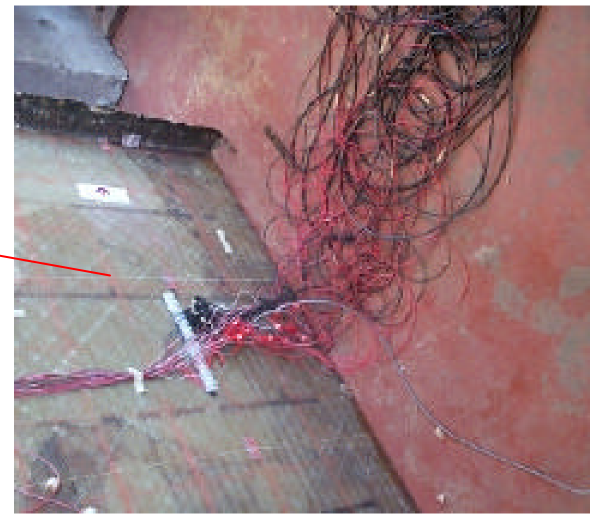
Experimental Setup
(Single Excitation With Multiple MEMS Sensors)

Objective: **Automated Prognostics**

Approach: **Substitute multiple hitting points with sensors (15 x 9=135), actuate limited number of locations**





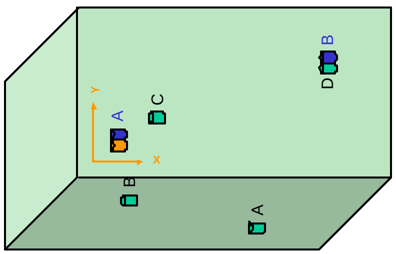


Shift a column of
15 MEMS sensors

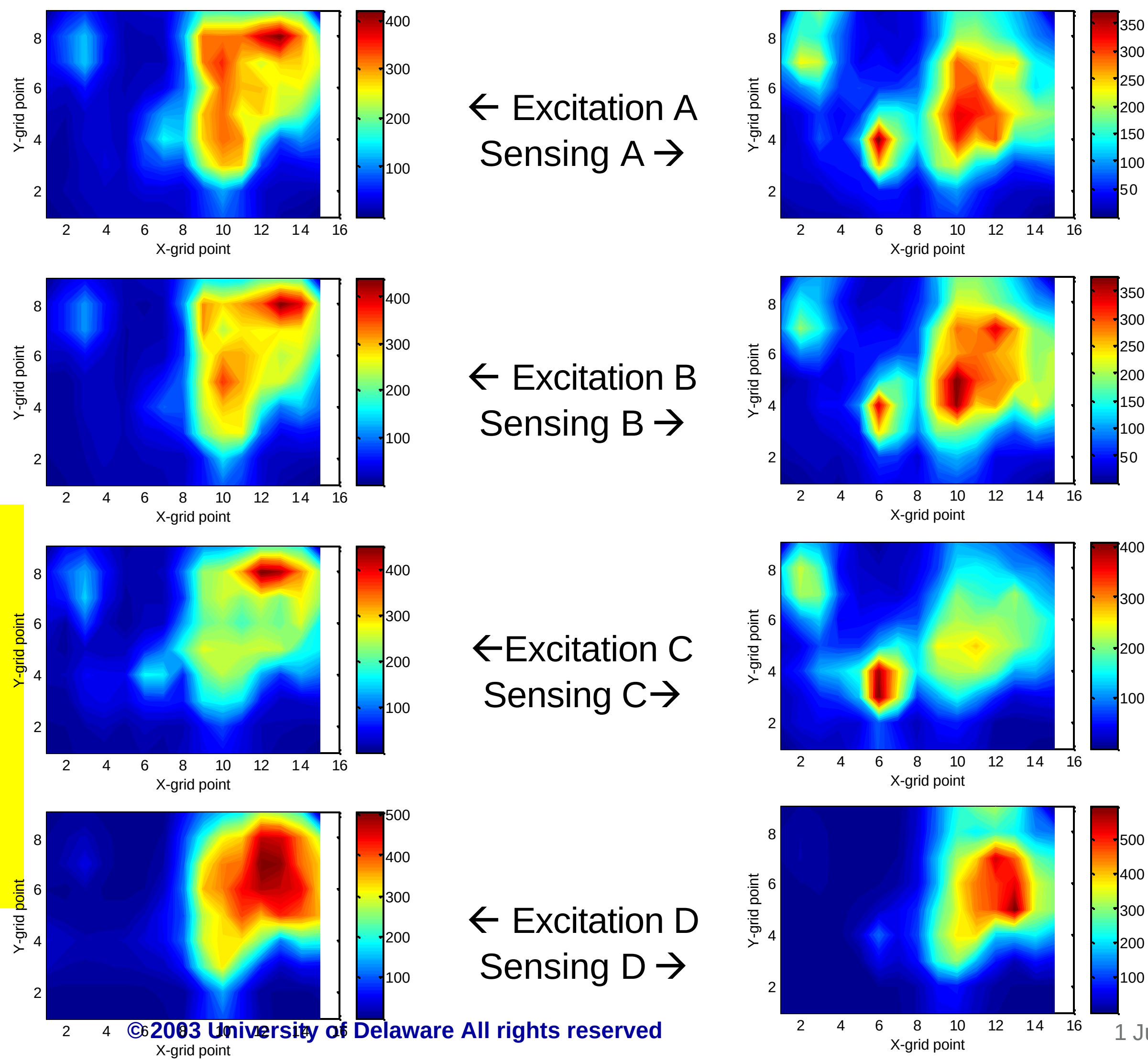
Limitations:
➔ Many sensor wires and connections

Solution:
➔ Wireless sensing system
➔ Sensors on fibers "SMART Structure"

Results for CIRTM Structure
(15 MEMS sensors: 15x9 grids, 100~1kHz)



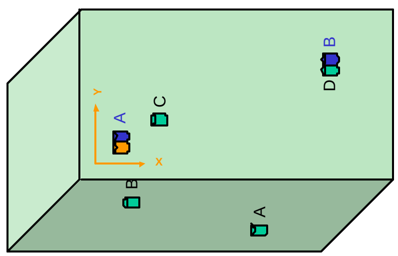
'NEW' Excitation at one location **'Classic' Sensing at one location**



Results:

- New method is less sensitive to small damage than classic method
- Approach has been proven, inverting hitting location to sensor location works

Results for CIRTM Structure
(15 MEMS sensors: 15x9 grids, Frequency range)

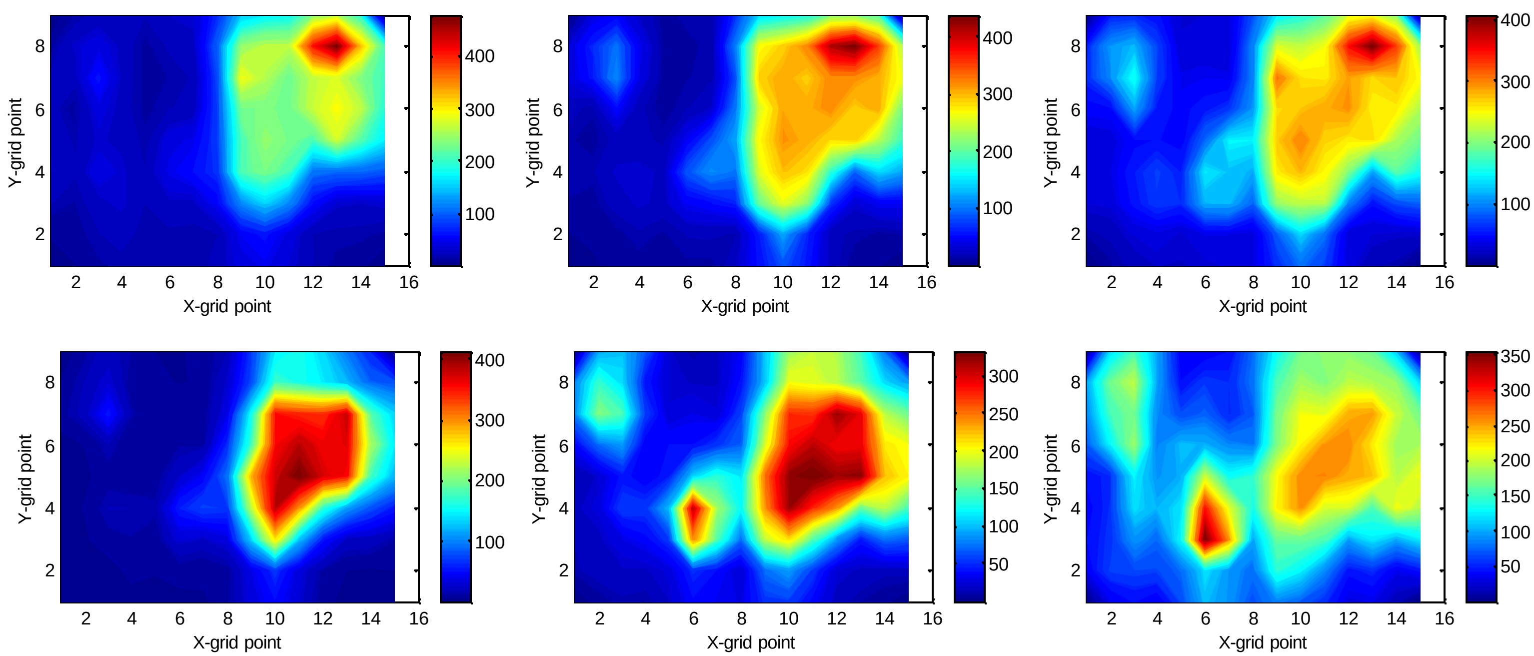


SII with sensors A+B+C+D (15 by 9 grids)

50~500Hz | 100~1kHz | 100~2kHz

Excitation at one location (New) ➡

Sensing at one location (Classic) ➡



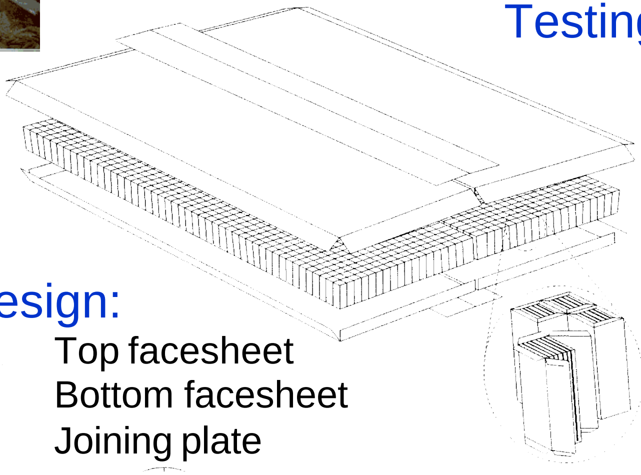
Results: Resolution not as good as classic method with accelerometer but acceptable
➔ Improved frequency spectrum of sensor and robust wiring will improve results

Large-Scale Structure
(Composite Bridge)

NDI Approach:
1. Visual inspection
2. Global NDI testing using vibration techniques ➔ Find anomalies, changes over time
3. Zoom in ➔ Local NDI techniques

Construction

Testing

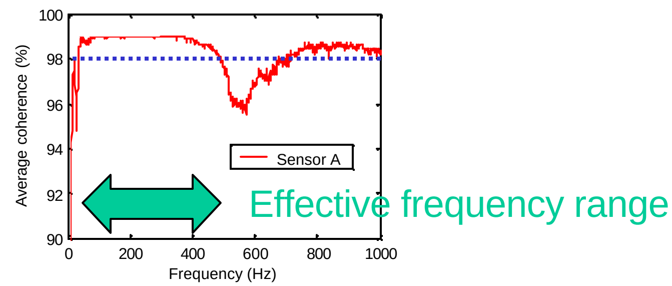


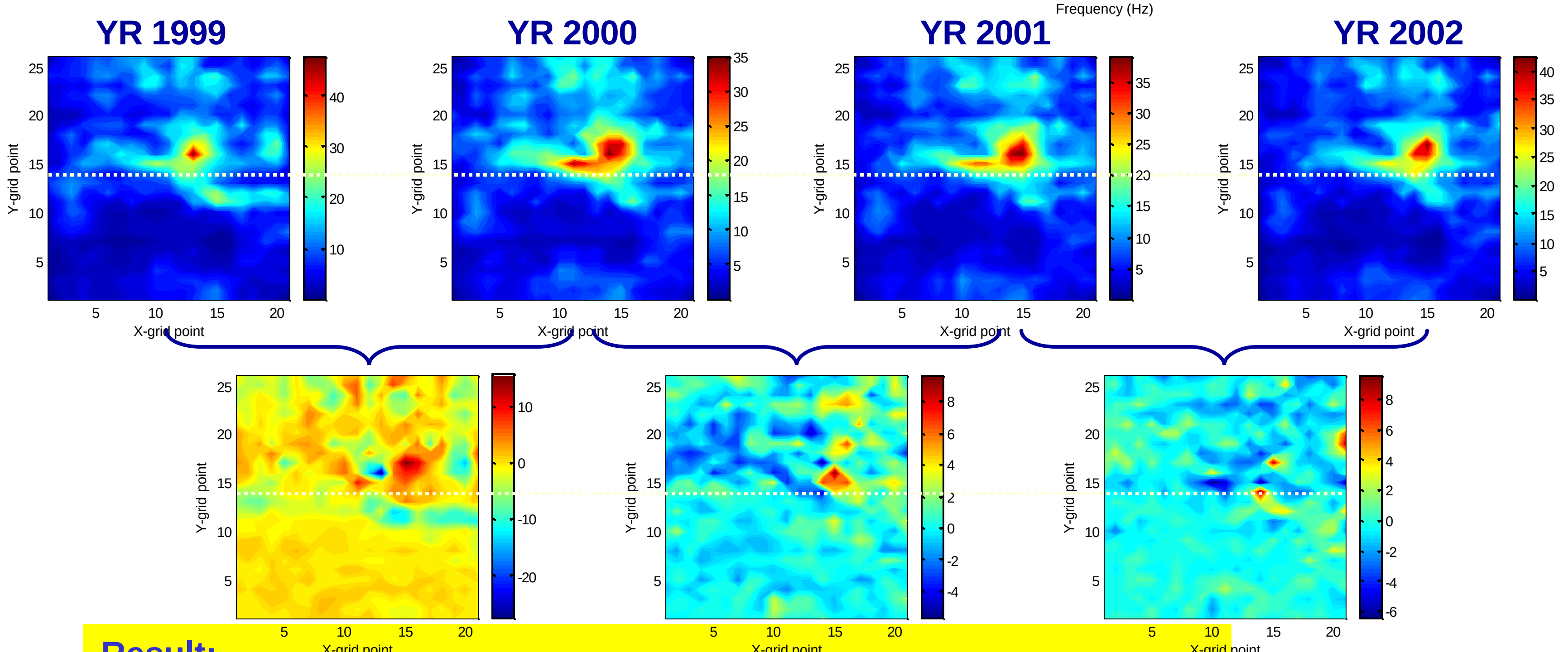
Design:
1. Top facesheet
2. Bottom facesheet
3. Joining plate

Results With Year

Frequency range: 50~500Hz
Data from sensor A
Dotted line: Joint line with splice plate

Coherence Function (YR 2002)





Result:
- All the tests show anomaly near joint line
- Anomaly does not change after initial settling in the first year
- Overall change is small in the following years
- Recommendation: Evaluate local anomaly with other NDI techniques

Data courtesy of Ratcliffe + Crane

Conclusion

Work done:

- Modified 2-D Gapped Smoothing Method
  - Statistically treatment with outlier detection method
- Compared advanced sensors: MEMS & fiber optic strain sensors
- Applied to large-scale composite structures

Issues addressed:

- Large vs. small size of damage
- Definition of damage index (Square vs. absolute of curvature difference)
- Compared MS and ODS data
- Effects of locations of sensors and excitation
- Effects of frequency range
- Multi-excitation with single sensing vs. multi-sensing with single excitation

Ongoing And Future Work

ALGORITHM IMPROVEMENT

- Current algorithm improvement using generic smoothing techniques
- New algorithm for quantitative estimation of stiffness changes with baseline data obtained from FE model
- System integration with Labview programming using ActiveX (LABVIEW+MATLAB+OROS FFT Analyzer+MEScope Modal Analysis SW)
- New algorithm enabling reduced number of sensors with baseline data obtained from FE model

ADVANCED ACTUATORS AND SENSORS

- Piezoelectric actuators
- Fiber optic strain sensors
- Magneto-strictive strain sensors
- MEMS accelerometers
- Sensors on fiber

AUTOMATION OF DAQ AND DATA PROCESSING

- Wireless sensing

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